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Transfer Function Computation for Complex Indoor Channels Using Propagation Graphs

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***Abstract*—This paper presents a low complexity method for computation of the transfer matrix of wireless channels in complex indoor environments using propagation graphs. Multi-room indoor environments can be represented in a vector signal flow graph with with rooms in the complex structure as nodes and propagation between rooms as branches. The transfer matrix can be computed using Masons theorem which lead to a much-reduced computational complexity.**

I. Introduction

Propagation graphs (PGs) offer a flexible structure for modelling multlink channels with account for multiple scattering. PGs describe the channel as a directed graph with the transmitters, receivers and scatterers as vertices and interactions between vertices as time-invariant transfer functions. Based on the graph description, closed-form expressions for the channel transfer function is given in [1].

The PG model have been applied to different scenarios including: millimetre wave [2], indoor to outdoor [3], polarized [4], and high speed railway [5] channel. However, as a result of the matrix inversion in the closed form expression, the computing requirement for implementing the PG model increases with increasing number of scatterers, thereby making the model unattractive for large environments such as large buildings, indoor office and even outdoor environments where the scattering region and hence, the number of scatterers is large.

In this paper, we propose a reduced complexity equivalent of the PG model for complex indoor environments comprising of a number of adjacent rooms. The PG for the environment is transformed into a vector signal flow graph (VSFG) with the rooms as nodes. A closed form expression is then derived for the channel's transfer matrix by applying a matrix equivalent of Mason's rule to the VSFG.

II. Propagation Graph Model

In this section, we introduce the propagation graph based model presented in [1]. We consider a simple directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with vertex set $\mathcal{V} = \mathcal{V}_\mathrm{t} \cup \mathcal{V}_\mathrm{s} \cup \mathcal{V}_\mathrm{r}$ which is a union of three disjoint sets: a set of transmitters, $\mathcal{V}_\mathrm{t}$, a set of scatterers, $\mathcal{V}_\mathrm{s}$ and a set of receivers, $\mathcal{V}_\mathrm{r}$. Wave propagation between the vertices is modelled by edges in $\mathcal{E}$. An edge, $e = (v, w)$, exists if and only if a wave can propagate directly from v to w. The propagation graph exhibits a special structure; transmit vertices have no incoming edges; receive vertices have no outgoing edges; and there are no loops in the graph, i.e., no edge, $e = (w, w)$ is possible between the same vertex, w. It should however be noted that cycles may exist in the graph.

Wave propagation in the graph is defined by the actions of the scatterers and edges. A scatterer re-emits weighted version of the sum of signals arriving via the incoming edges to the outgoing edges. An edge $(v, w) \in \mathcal{E}$ transfers a signal from v to w according to its transfer function, $A_{(v,w)}$. We set $A_e(f) = 0$ for $e \notin \mathcal{E}$. The edge transfer functions are collected into sub-matrices:

$$\begin{aligned}
\mathbf{D}(f) &: \text{transmitters} \to \text{receivers} \\
\mathbf{T}(f) &: \text{transmitters} \to \text{scatterers} \\
\mathbf{R}(f) &: \text{receivers} \to \text{scatterers} \\
\mathbf{B}(f) &: \text{scatterers} \to \text{scatterers.}
\end{aligned}$$

Assuming that the channel is time-invariant, the transfer matrix, $\mathbf{H}(f)$ of the propagation graph can be expressed in closed form as [1]

$$\mathbf{H}(f) = \mathbf{D}(f) + \mathbf{R}(f)[\mathbf{I} - \mathbf{B}(f)]^{-1}\mathbf{T}(f), \tag{1}$$

provided that the spectral radius of $\mathbf{B}(f)$ is less than unity.

III. PG for Multi-room Indoor Environments

Consider a building comprising of N adjacent rooms as illustrated in Fig. 1. Assuming that each room has N_s scatterers, the entire building can be represented using a propagation graph with $M = NN_\mathrm{s}$ scattering vertices. The channel between transmitters and receivers in any of the rooms can be computed using (1). This requires inversion of an $M \times M$ matrix and as such becomes computationally intensive with increasing number of

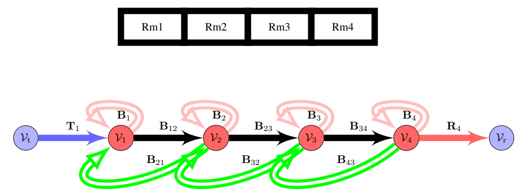

Fig. 1: VSFG of a four-room building with the transmitter(s)(receiver(s)) are in room 1(4).

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TABLE I: Simulation Parameters.

Parameter	Value	Parameter	Value
Room sizes	$3 \times 4 \times 3\,\mathrm{m}^3$	g	0.62
Freq. range	$58\,\mathrm{GHz} - 62\,\mathrm{GHz}$	P_{vis}	0.90
Numb. of samples	801	N_{s}	10

TABLE II: Averaged total power, mean delay and RMS delay spread with two wall penetration factor values.

η	Total Power [dB]			Mean Delay [ns]			RMS DS [ns]		
	PG	VG1	VG2	PG	VG1	VG2	PG	VG1	VG2
0.4	-120.8	-120.8	-120.6	25.6	25.6	26.7	8.6	8.6	10.1
0.8	-114.6	-114.6	-114.4	26.3	26.3	27.5	9.8	9.7	11.5

rooms and/or scatterers. To overcome this limitation, we represent the propagation graph as a VSFG as in Fig. 1. The VSFG can be constructed from the environment floor plan and/or PG by applying the following rules:

- Each room is designated as a node with a loop corresponding to the interactions between scatterers within the room.
- Inter-room propagation through walls are represented as branches between the nodes.

We denote the transfer matrix from scatterers in room n to m as $\mathbf{B}_{nm}$. For $n = m$, the matrix designates within room scattering. For $n \neq m$, the matrix designates propagation between rooms and should be scaled with a multiplicative wall penetration factor, η. Let $\mathcal{K}$ denote the set of all cycles in the VSFG, including loops. Here we exclude circular permutations and include each cycle only once. For cycle $k \in \mathcal{K}$ we define the cycle transfer function L_k as the product of all edge transfers along the cycle. The transfer function of inter-room loops is taken as the post-multiplication of the forward inter-room transfer matrix by the reverse transfer matrix. The channel transfer function between transmitters in room n and receivers in the mth room can be obtained by applying a matrix equivalent of Mason's rule to the VSFG as

$$\mathbf{H}_{nm}(f) = \mathbf{D}_{nm}(f) + \mathbf{R}_m(f)\mathbf{\Sigma}(f)^{-1}\mathbf{P}_{nm}(f)\mathbf{T}_n(f) \quad (2)$$

where $\mathbf{R}_m$ and $\mathbf{T}_n$ denote the transfer function of edges from scatterers in the mth room to the receiver(s) and from the transmitter(s) to scatterers in the nth room, respectively. $\mathbf{P}_{nm}(f) = \prod_{i=n}^{m-1} \mathbf{B}_{i,i+1}$ is the product of all transfer functions on the forward path between the transmitting and receiving rooms and $\mathbf{\Sigma}(f)$ is defined as

$$\mathbf{\Sigma}(f) = \mathbf{I} - \sum \mathbf{L}_k + \sum \mathbf{L}_i\mathbf{L}_j - \sum \mathbf{L}_i\mathbf{L}_j\mathbf{L}_k + \ldots . \quad (3)$$

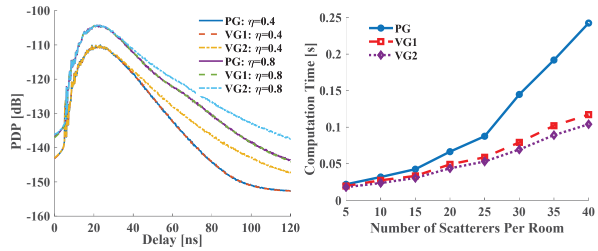
Here, the first sum is taken over all loop transfer functions, the second over all products of any two non-touching loops, third over all products of three non-touching loops and so on. Notice that the dimension of all matrices in (3) is $N_{\mathrm{s}} \times N_{\mathrm{s}}$.

Since the computation of the PG in (1) and its VSFG equivalent in (2) is dominated by the matrix inversion operation, the PG and VSFG have approximate complexity of $\mathcal{O}((NN_{\mathrm{s}})^3)$ and $\mathcal{O}(N_{\mathrm{s}}^3)$, respectively.

IV. Simulation and Results

In this section, we illustrate the potentials for complexity reduction for the PG models. We consider a two rooms building with the transmitter in room 1 and receiver in room 2. The channel is generated following the procedures highlighted in [1] with the parameters in Table I. The scatterers are uniformly distributed within the volume of the rooms. For the two rooms building, the expression in (3) becomes

$$\mathbf{\Sigma}(f) = \mathbf{I} - (\mathbf{B}_{11} + \mathbf{B}_{22} + \mathbf{B}_{12}\mathbf{B}_{21}) + \mathbf{B}_{11}\mathbf{B}_{22}. \quad (4)$$



(a) Simulated PDS (b) Computer Time.

Fig. 2: The simulated power delay spectrum and computation time for 801 responses.

We compare three implementations of the model viz: the original graph model in (1) (PG) and the VSFG using (2) with (VG1) and without (VG2) the third term in (4). As expected, we observed in Fig. 2 that VG1 produces the same averaged power delay profile as the PG at a lower computation time. Similar observation is seen in Tab. II where the averaged total power, mean delay and root mean square (RMS) delay spread for both the PG and VG1 are approximately equal. As seen in Fig. 2, eliminating the third term of (4) (i.e., VG2) decreases the decay rate of the PDP. Slight decrease in total power and increase in both the mean delay and RMS delay spread is observed for VG2 in Tab. II. The averaged frequency correlations (not shown here) is observed to be approximately equal for all three implementations of the model.

V. Conclusion

A low complexity implementation of the propagation graph model is proposed via a representation of the complex environment as matrix signal flow graph. Simulation results show that the VSFG equivalent yield same prediction of the channel as the original model with much lower computational complexity. Our ongoing work is generalizing the model to more realistic building structures.

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